Reducing Influence of Bias Stress on AMOLED Displays by Driving in Linear Regime: a Sensitivity Perspective

Florian De Roose[*†‡], Kris Myny[†], Jan Genoe[†*], Paul Heremans[†*] and Wim Dehaene[*]
[*] Department of Electrical Engineering (ESAT), KU Leuven, Kasteelpark Arenberg 10, 3001 Heverlee, Belgium
[†] Large Area Electronics Department, imec, Kapeldreef 75, 3001 Heverlee, Belgium
[‡] E-mail: Florian.DeRoose@esat.kuleuven.be, tel: +32 16 32 86 18

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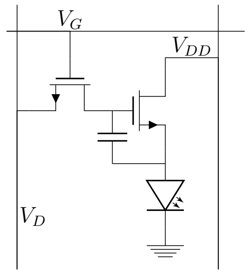
***Abstract*—We present analytical equations to calculate the sensitivity of AMOLED displays to degradation of the electric characteristics of both the transistor and OLED. These equations can be applied to any technology using 2T1C pixels. They show that digital driving is less sensitive to bias stress.**

I. Introduction

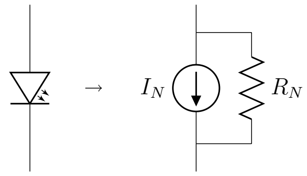
In recent years, OLEDs have come to be one of the main technologies for the manufacturing of displays. OLEDs have several advantages over traditional LCD displays, like vivid colors, better dark levels, implementable on flexible foil and intrinsically lower energy consumption. Yet current OLED displays do not fully exploit this, as most active matrix OLED (AMOLED) displays use an analog backplane to control pixel brightness. An analog thin film transistor (TFT) in saturation is used to limit the current through the pixel, thereby requiring a V_{DS} larger than $V_{GS} - V_T$ and hence consuming a lot of energy. The energy lost in this way can go up to 50% of the total energy consumption. The only way to reduce this power consumption is by lowering the V_{DS} across the TFT, i.e. by using the transistor in linear regime. This is most commonly associated with a digital switch, although not exclusively. In the implementation of PWM (pulse width modulation) techniques for display driving, people have struggled to get sufficiently high duty cycles and number of bits [1]–[3]. Genoe et al. presented a digital PWM-driven AMOLED display using an advanced encoding strategy, thereby allowing the TFT to be effectively used as a switch [4]. In order to garantuee the highest resolution possible, the 2T1C pixel, depicted in figure 1a, is used. This paper will compare the sensitivity of the different drive concepts. The equations which are derived, are useful as a designers' guideline, both for evaluating designs and choosing the right design approach, i.e. digital or analog driving.

II. Analysed situation

In figure 2 the analysed schematics are shown. The traditional circuit consists of a supply which is common for all pixels, a drive TFT and an OLED. The OLED is nearly always connected to ground for technological reasons. This circuit is shown in figure 2a. Since in an



(a) The 2T1C pixel



(b) Norton equivalent of an OLED

Fig. 1. Figure 1a shows the 2T1C pixel schematics, which is the most compact pixel engine conceivable. Figure 1b shows the Norton equivalent of the OLED, which is used to simplify small signal analysis of the component.

ideal situation all pixels are identical and independent, only one pixel needs to be studied. The all-digital PWM-driven solution according to [4] consists of one current source per column, and is shown in figure 2b. The impedance of the other pixels will convert the current in a voltage.

Because a sensitivity analysis is a small-signal analysis, we can replace the OLED by its Norton equivalent, as shown in figure 1b and describe its behaviour by the output impedance R_{N} and the Norton current $I_{\mathrm{N}} = I_{\mathrm{OLED}} - V_{\mathrm{OLED}}/R_N$. Degradation of the OLED will cause a shift in voltage and a decrease in current, which can both be mathematically modeled by a shift in I_{N}.

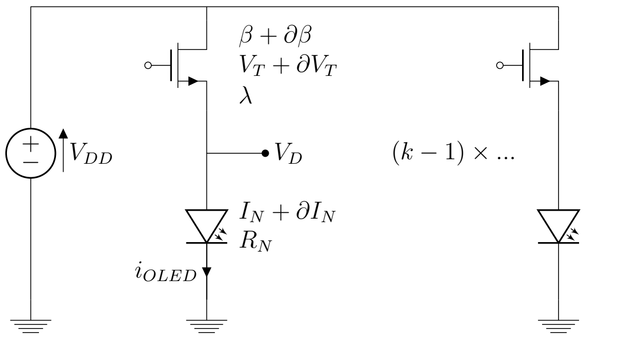
In order to keep the analysis both general in nature (technology independent) and simple, we use a very compact model for the TFT. In saturation, an α-law model with output resistance is used:

$$I_{DS} = K\frac{W}{L}V_{GST}{}^{\alpha}\left(1+\lambda V_{DS}\right) \tag{1}$$

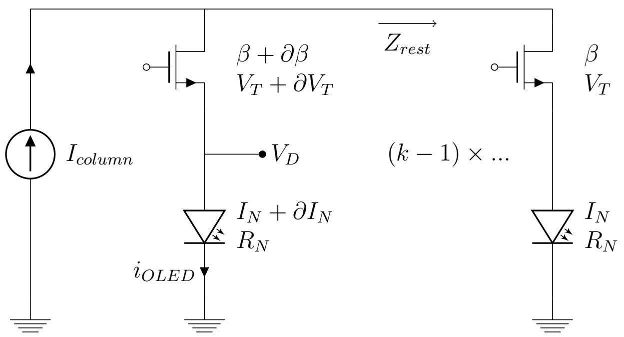
with $V_{GST} = V_G - V_S - V_T$. The linear regime is modeled by the superposition of two of those currents flowing in opposite directions:

$$I_{DS} = K\frac{W}{L}\left[V_{GST}{}^{\alpha} - V_{GDT}{}^{\alpha}\right] \tag{2}$$

with $V_{GDT} = V_G - V_D - V_T$. The factor KW/L is written as β for brevity. Table I shows the technology parameters used for numerical analysis.



(a) Conventional driving



(b) Digital driving

Fig. 2. Figure 2a shows the analysed schematic for conventional driving, figure 2b shows the analysed schematic for digital driving [4].

α	2.3
V_T	-1 V
K	90 nA/V$^\alpha$
R_N	1.13 MΩ
I_N	2 µA
V_OLED	4.02 V

TABLE I
TECHNOLOGY CONSTANTS

III. Design options

For both analog and digital driving, there are a limited number of design parameters that are optimised.

The design parameters in an analog driven display are the maximal V_{GS} for full brightness and distance of the V_{DS} to V_{DSsat}. The latter parameter is usually chosen by process variations, and has, aside from the power consumption, little effect on the circuit, as long as the transistor stays in saturation. Larger V_{GS} will lead to smaller W/Ls and larger V_{DS}, and therefore more power consumption. In order to have enough current, $V_{GS} - V_T$ is chosen above 4V for a-IGZO panels, which is a fair assumption for a comparison of the designs [5].

For digital driving there are also two design parameters: V_{GS} and V_{DS}. In this case V_{GS} will often be determined by the supply voltage which is used in the rest of the display. As an example, we will use both $V_{GS} = 10$V and $V_{GS} = 15$V. V_{DS} will determine how deep the transistor is in linear regime. Lower V_{DS} will mean a larger transistor, less power consumption and makes the transistor act more like an ideal switch. Figure 3 shows the size of the transistor in function of the V_{DS} for our technology.

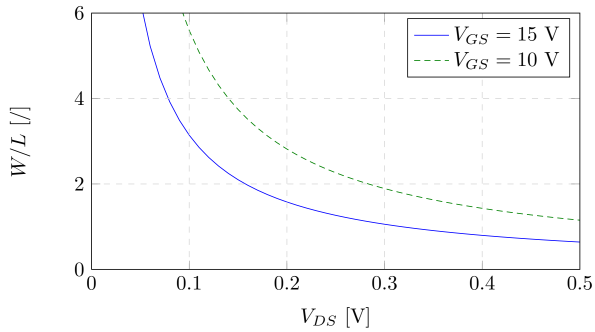


Fig. 3. Size of the drive transistor in function of the drain voltage in linear regime, for the given a-IGZO technology.

IV. Mathematical analysis

First consider the case of conventional driving. In this case, the sensitivities can be calculated by partial derivation of the equations extracted from the given schematic. All sensitivities have a common factor ζ:

$$\zeta_{SAT} = \frac{1}{1 + \beta {V_{GST}}^{\alpha-1} R_\text{N}(\alpha + \lambda\alpha V_{DS} + \lambda V_{GST})} \tag{3}$$

$$\approx \frac{1}{1 + \alpha\beta {V_{GST}}^{\alpha-1} R_\text{N}} \tag{4}$$

$$\approx \frac{1}{1 + \alpha i_\text{OLED} R_\text{N} / V_{GST}} \tag{5}$$

The relevant parameters for which the sensitivity can be calculated are threshold voltage V_T, mobility μ and the current through the OLED at a given voltage. These can be related to the electrical properties of the pixel design, respectively V_{GT}, β and I_N. The sensitivities can then be calculated as:

$$\frac{\partial i_\text{OLED}/i_\text{OLED}}{\partial V_T} = -\frac{\partial i_\text{OLED}/i_\text{OLED}}{\partial V_{GT}} = \frac{-\alpha}{V_{GST}}\zeta_{SAT} \tag{6}$$

$$\frac{\partial i_\text{OLED}/i_\text{OLED}}{\partial \mu/\mu} = \frac{\partial i_\text{OLED}/i_\text{OLED}}{\partial \beta/\beta} = \zeta_{SAT} \tag{7}$$

$$\frac{\partial i_\text{OLED}/i_\text{OLED}}{\partial I_\text{N}/I_\text{N}} = -\left(1 - \zeta_{SAT}\right) \tag{8}$$

For the linear regime, assuming a digital driving scheme, the equations get slightly more complex, but the results are similar. The analysis results in the following equations. Again, there is the same common factor ζ.

$$\zeta_{LIN} = \frac{k-1}{k} \frac{1}{1 + \alpha\beta {V_{GST}}^{\alpha-1} R_\text{N}} \tag{9}$$

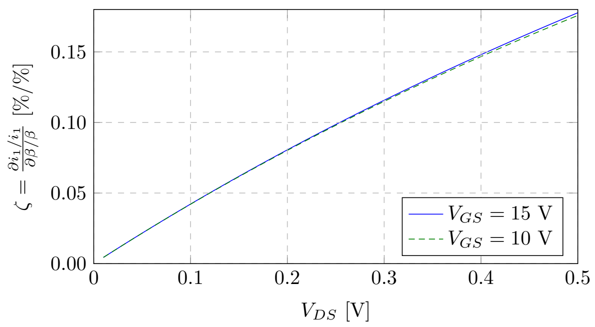


Fig. 4. Sensitivity of the current through the OLED to variation in β, depending on V_{DS} and V_{GS} in linear regime, for the given a-IGZO technology

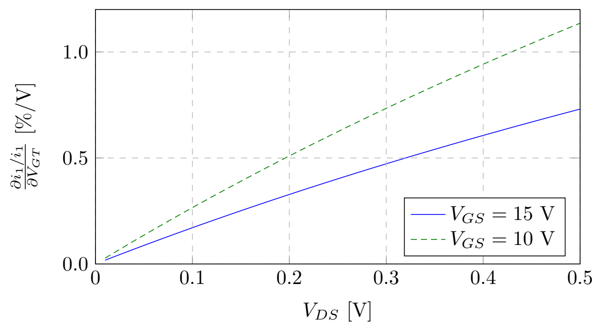


Fig. 5. Sensitivity of the current through the OLED to variation in V_T, depending on V_{DS} and V_{GS} in linear regime, for the given a-IGZO technology

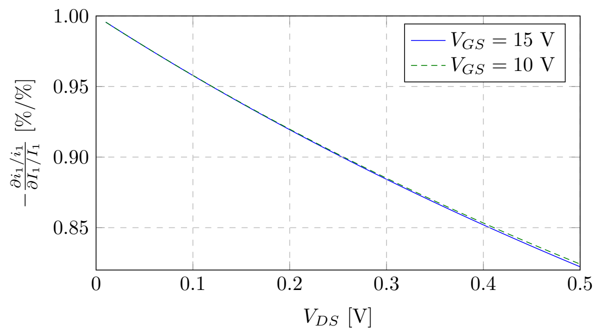


Fig. 6. Sensitivity of the current through the OLED to variation in I_{N}, depending on V_{DS} and V_{GS} in linear regime, for the given a-IGZO technology

This factor is the same as for conventional driving, save from a factor $(k-1)/k$, which can be approximated 1 for a large number of pixels.

$$\frac{\partial i_{\mathrm{OLED}}/i_{\mathrm{OLED}}}{\partial V_{GT}} = \alpha\zeta_{LIN}\frac{V_{GST}{}^{\alpha-1} - V_{GDT}{}^{\alpha-1}}{V_{GST}{}^{\alpha} - V_{GDT}{}^{\alpha}} \quad (10)$$

$$\frac{\partial i_{\mathrm{OLED}}/i_{\mathrm{OLED}}}{\partial \beta/\beta} = \zeta_{LIN} \quad (11)$$

$$\frac{\partial i_{\mathrm{OLED}}/i_{\mathrm{OLED}}}{\partial I_{\mathrm{N}}/I_{\mathrm{N}}} = -\left(1 - \zeta_{LIN}\frac{k}{k-1}\right) \quad (12)$$

$$\approx -\left(1 - \zeta_{LIN}\right) \quad (13)$$

V. Interpretation

A. Interpretation of the equations

These equations can also be derived in a different way. Variation of the parameters can be interpreted as an injection of a small signal current or voltage, depending on the changing parameter. The common factor ζ is as such essentially the source degeneration of an amplifying stage, equal to $1/(1+g_m R_S)$. A change in threshold voltage is then equivalent to injection of a small signal to the gate, and is amplified by g_m and then degenerated by ζ.

An interesting observation is that the sensitivity to β and the sensitivity to I_{N} are linearly coupled. Decreasing one will inevitably increase the other one. This is mainly caused by the source follower topology, which introduces a large influence of the OLED properties on the total current. The more the OLED degenerates the transistor (smaller ζ), reducing the sensitivity to transistor parameters, the larger the influence of the OLED itself. It is therefore impossible to make a pixel that is both insensitive to variations in the transistor and in the OLED.

In figure 4, 5 and 6, the sensitivities of a digitally driven display are shown depending on how deep in the linear regime the transistors are operated. Table II compares an analog, a moderately digital and a strongly digital systems in terms of sensitivity.

B. Application of the sensitivities

Knowing an analytical description of the sensitivities has several uses. First of all, it gives designers a tool to evaluate their designs, and redesign if the pixel is too sensitive to variations. Secondly it helps technology developers focus on the most important source of variation.

Finally it can be used to compare conventional analog driving in saturation to digital driving in linear regime. For this purpose, a value for the expected variation of the OLED and the transistor is needed. Assuming that the most important source of variation in the TFT is V_T shift due to bias stress, an increase of 0.874V after 10^5s can be expected from Hayashi et al., a state-of-the-art technology for TV purposes [6]. For the OLED, most papers present accelerated degradation by increasing the current density. According to Yoshioka et al. the lifetime scales with $1/\tau \propto J^{\beta}$, with β = 1.42 for 25°C [7]. Hai In et al. [8] showed lifetime characteristics for a current of 173.4 mA/cm^2, instead of the 2.5 mA/cm^2 for the design example. According to Yoshioka et al. the time scale can therefore be increased by a factor of 411. After 10^5s, an increase of V_{OLED} of 2.3mV can be expected, corresponding to a relative current decrease of 0.1%, based on the technology parameters given in table I. No

	Analog	Moderate digital	Strong digital
Sensitivity to ΔV_T	25 $\frac{\%}{V}$	1.1 $\frac{\%}{V}$	0.33 $\frac{\%}{V}$
Sensitivity to $\Delta\mu/\mu$	0.43 $\frac{\%}{\%}$	0.18 $\frac{\%}{\%}$	0.081 $\frac{\%}{\%}$
Sensitivity to OLED current	0.57 $\frac{\%}{\%}$	0.82 $\frac{\%}{\%}$	0.92 $\frac{\%}{\%}$
Current drop after 10^5s	21.9%	1.04%	0.38%

TABLE II
OVERVIEW OF SENSITIVITIES IN THREE CASES: ANALOG (V_{GS}=4V, V_{DS}=6V), MODERATE DIGITAL (V_{GS}=10V, V_{DS}=0.5V) AND STRONG DIGITAL (V_{GS}=15V, V_{DS}=0.2V). THE ESTIMATED STATE-OF-THE-ART VARIATIONS ARE $\Delta V_T = 0.874$V [6] AND $\Delta I_1/I_1 = 0.1\%$ [7], [8] AFTER 10^5S. THE SHIFT IN MOBILITY HAS NOT BEEN INCLUDED IN THE CURRENT DROP CALCULATION BECAUSE NO RELEVANT DATA IS AVAILABLE.

clear data on mobility degradation could be found in literature, so it is not included in the evaluation.

When we introduce the degradation data from [6]–[8], we can assess the effect of the different contributions after 10^5s. In table II an overview for the three scenarios is presented. It is clear that the shift in V_T of the TFT due to bias stress is much more influential than the shift in electrical properties of the OLED. Therefore, it can be concluded that a design which uses the TFT as a digital switch, rather than an analog source follower will be less sensitive to degradation.

VI. CONCLUSION

This paper shows analytical equations for the sensitivity of AMOLED pixels to TFT and OLED degradation, for TFTs working both in linear and in saturation regime and indicates the parameters involved. A one-to-one comparison showed the relative magnitude of the contributing components, showing that V_T-shift is the dominant factor. A pixel scheme in linear regime, i.e. using a digital driving scheme is nearly 2 orders of magnitude more robust against the expected parameter variations.

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